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VOLUMETRIC SIMILARITY FOR VIBRATIONS OF REED VALVE IN REFRIGERANT COMPRESSORS

by

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ABSTRACT

The cylinder shape of the rotary compressors is naturally quite different from that of the reciprocating compressors. However, if the Helmholtz in-flow resonance frequency of a resonator composed of the cylinder and the discharge port takes on a same value for both the reciprocating and rotary compressors, the reed valve will exhibit a similar vibration feature. First, forced vibration tests for a reed valve were made to examine the pressure pulsations in the discharge port. Secondly, free vibration tests for a reed valve were made. Conclusively, similar data were obtained both for the reciprocating and rotary compressors, thus ensuring a volumetric similarity for vibrations of the reed valve in refrigerant compressors.

INTRODUCTION

It is frequently stated that the major sources of the noise in refrigerant compressors are the electromagnetic vibrations of the motor inducing motor noises, the elastic vibrations of the reed valve inducing valve noises, the pulsating flow of refrigerant gas inducing gas impulse noises, the slap motion of the piston inducing piston-slap noises, and the elastic vibrations of the crankshaft inducing crankshaft noises (Imaichi & Ishii *et al.* 1984 /1/). The present study is concerned with vibrations of the reed valve.

From a basic standpoint that the self-excitation mechanism of reed valves in refrigerant compressors used for air conditioners or refrigerators should be clearly addressed, forced vibration tests for a reed valve exposed to an air jet from a reciprocating-type resonator model, shown in Figure 1, were conducted by Ishii *et al.* (1993 /2/): the resonator model is composed of the valve plate, the cylinder and the piston; the reed valve is replaced by a column which was forced to vibrate by a magnetic exciter, in the frequency range from 50 to 500 Hz; the air pressure pulsations in the resonator were measured to reveal its frequency characteristics and spatial distribution, in amplitude and in phase-lag relative to the valve vibration; the similar measurements were performed for various cylinder volumes. As a result, it was revealed that the air pressure pulsations in the resonator are quite subject to the volumetric air vibrations and are significantly determined by the frequency ratio of reed valve vibration to Helmholtz resonance, thus resulting in a dynamic stability criterion that the reed valve never induces any self-excited vibration if the frequency ratio is larger than 1.0. Additionally, free vibration tests for the reed valve also were made to demonstrate the dynamic stability criterion.

Subsequently, more detailed forced vibration tests for the reciprocating-type resonator model were made to reveal a mechanism for the reed valve to induce self-excitations, by Ishii *et al.* (1994 /3/) As a result, it was revealed that the air pressure pulsations in the discharge port are significantly affected by a dynamic response of the contraction of discharge port flow to the valve displacement: if the frequency ratio of reed valve vibration to Helmholtz resonance is smaller than 1.0, with increasing the valve opening, the contraction of flow increases due to a mass flow effect, thus squeezing the discharge port flow; thus increasing the discharge port pressure; thus pushing the valve in the same direction to open; thus resulting in a self-excitation.

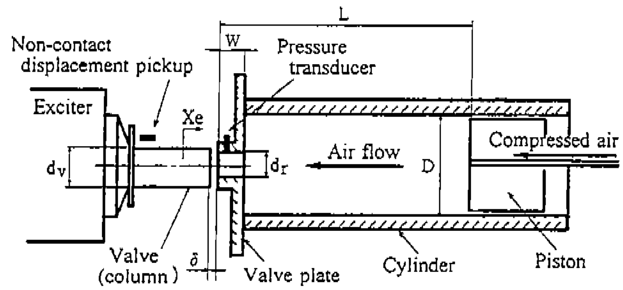

Figure 1. Reciprocating-type resonator model for forced vibrations of reed valve.

Of quite significance here is a conclusion that the air pressure pulsations in the reciprocating-type resonator model are quite subject to the volumetric air vibrations, suggesting a volumetric similarity that major factors for vibrations of the reed valve show a similar feature if the Helmholtz in-flow resonance frequency is same. If this conclusion is truly correct, all of the results obtained for the reciprocating-type resonator model can effectively be applied to the rotary-type compressors with the half-crescent-shaped cylinder, quite different from the axisymmetrical cylinder of the reciprocating type. Therefore, the volumetric similarity between the reciprocating and rotary types is better to be directly demonstrated. This study presents forced and free vibration test results for the rotary-type resonator model. The forced vibration tests reveal the entire characteristics of the air pulsations at the discharge port: the phase-lag relative to the reed valve vibration and its amplitude. The free vibration tests reveal an excitation ratio of the reed valve and its in-flow vibration frequency. Results obtained for the rotary type are compared with those for the reciprocating type.

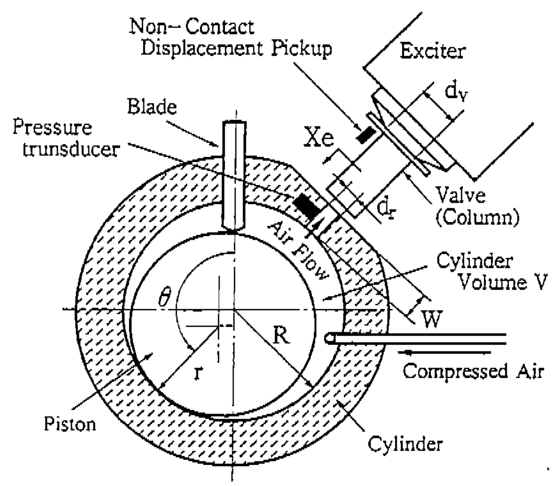

Figure 2. Rotary-type resonator model for forced vibrations of reed valve.

ROTARY-TYPE RESONATOR MODEL

The upper frequency limit to vibrate the valve at an available amplitude, by a magnetic exciter, was about 500 Hz. The Helmholtz resonance frequency of the rotary type resonator has to be far under the frequency limit. Therefore, a fairly large-sized resonator model of the rotary type was needed to make, as shown in Figure 2, where the cylinder radius R was 56 mm, the cylinder depth was 110 mm, the rolling piston radius r was 46.5 mm and the blade thickness was 10 mm, thus resulting in a maximum cylinder volume of 377 cc. The discharge port has the same dimensions as the reciprocating type, shown in Figure 1: 8.7 mm for the bore d_r and 15 mm for its length W. The lowest value of the Helmholtz resonance frequency was about 175 Hz.

FORCED VIBRATION TESTS

For forced vibration tests, the practically used reed valve, shown in Figure 3, was replaced by a column, namely a valve, directly connected to a magnetic exciter, as shown in Figure 2. The valve with the same diameter d_v of 12 mm as the reed valve, was placed against the discharge port so that the mean opening height of the valve, δ, was 85 μm. The forced vibration amplitude of the valve was adjusted at 25 μm and its frequency was varied from 50 Hz to 500 Hz.

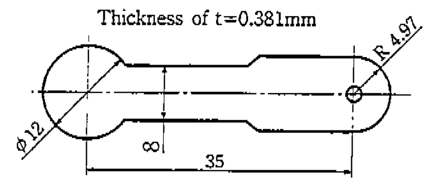

Figure 3. Reed valve and its major dimensions.

The air compressed at 4.9 kPa was fed into the cylinder through a small hole at the thrust plate. The bore of the hole was 3.4 mm, far smaller than other dimensions. The compressed air blows out through the gap between the valve and the outer surface of the valve plate. If the valve vibrates at this time, the discharge rate of the air alternately increases and decreases. This causes the compressed air pressure in the discharge port and the cylinder to fluctuate. The air pressure does not necessarily fluctuate without a phase lag, however, caused by an inertial effect of the mass flow of air, for example. A representative fluctuating air pressure was measured using a pressure transducer (TOYODA PD-104 S0.1F-1340) attached to the wall of the discharge port. In addition, the valve vibration was measured using a non-contact-type vibration transducer (IMV PB-0310).

The most significant quantity characterizing the discharge port air pressure is the phase-lag relative to the valve movement, which definitely determines whether the energy is supplied from the air to the valve. The phase lag of the pressure peak from the instant when the valve closes the discharge port, ϕ, was calculated from the measures pressures, as shown in Figures 4a to 4e, where the abscissa is the forcing frequency of the valve, F. The parameters are given by the rotating angle of the rolling piston, θ, shown in Figure 2, the corresponding cylinder volume V and the Helmholtz in-flow resonance frequency F_h. For any cylinder volume, the phase lag takes on positive values in the lower forcing frequency range. Since the air pressure with a positive phase lag mostly pushes the valve in the same direction as it moves, an energy transfer from the flow to the valve movement occurs. If the column is replaced back to the original reed valve, under this condition, the reed valve will be self-excited.

It is worthwhile emphasizing that the phase lag ϕ takes on plus and minus values depending on the forcing frequency F, and the forcing frequency at which the phase lag ϕ becomes zero increases as the cylinder volume V decreases. This property of the phase lag suggests a dependence on the Helmholtz resonance frequency F_h. It should be noted here that the Helmholtz resonance frequency for the resonator with flow as in the present subject was studied by Ishii *et al.* (1994 /3/) to find that due to the contraction of flow, the net mass of the discharge port decreases, thus resulting in a significant increase of namely the in-flow resonance frequency, compared with for the resonator without flow. The calculated values for the in-flow resonance frequency F_h are given in each diagram of Figures 4a to 4e. The reduction ratio of the discharge port to the cylinder depth, ξ, seriously affecting the contraction of flow at the discharge port, took on a value of 0.079 for the present rotary-type resonator model. Interestingly, the calculated in-flow resonance frequencies are in good agreement with the forcing frequencies at which the phase lag ϕ becomes zero, respectively. Thereupon, the values along the abscissa F of Figures 4a to 4e were divided by the corresponding value of the in-flow resonance frequency F_h and the phase lag ϕ was plotted again in Figure 4f using this nondimensional abscissa F/F_h. Interestingly, it can be seen from this figure that the phase lag at different values of the cylinder volume roughly lies on one curve, and near the frequency ratio $F/F_h = 1.0$, the phase lag changes sign.

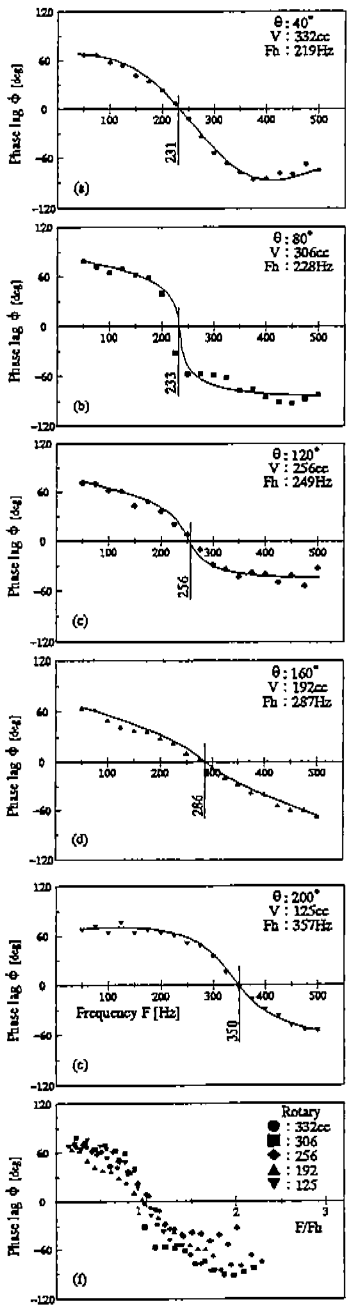

Figure 4. Forced vibration test results of discharge port pressure for rotary-type resonator model: (a) to (e) phase-lag relative to valve displacement, vs. forced vibration frequency; (f) phase-lags vs. frequency ratio of forced vibration to Helmholtz in flow resonance.

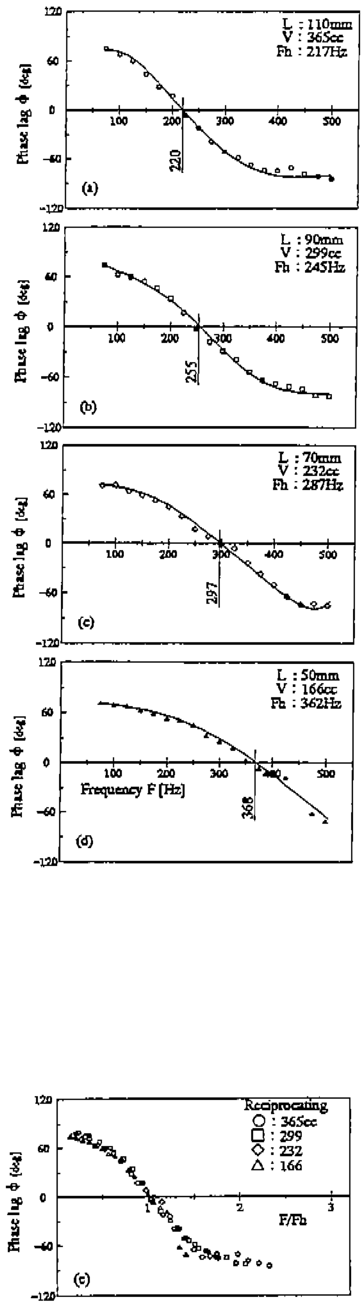

Figure 5. Forced vibration test results of discharge port pressure for reciprocating-type resonator model: (a) to (d) phase-lag relative to valve displacement, vs. forced vibration frequency; (e) phase-lags vs. frequency ratio of forced vibration to Helmholtz in flow resonance.

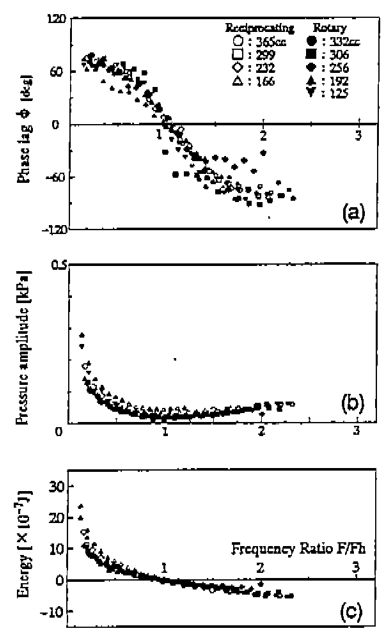

Figure 6. Comparison of discharge port pressures for reciprocating-type and rotary-type resonator models: (a) phase-lag; (b) amplitude; (c) energy supplied from the air flow to the valve.

Similar data measured for the reciprocating-type resonator model shown in Figure 1 are shown in Figure 5, citing Figure 2e in a study by Ishii *et al.* (1994 /3/). The cylinder diameter D of 65 mm was selected, since it resulted in 0.134 for the reduction ratio of the discharge port bore to the cylinder bore, ξ, which was most close to 0.079 for the rotary-type resonator model. It is seen from these figures that the phase lag both for the rotary and reciprocating types exhibits quite similar features. This result can be well ensured again in Figure 6a, where all data for the phase lag both for the rotary and reciprocating types are plotted. In addition, the amplitude data are all plotted in Figure 6b, showing a good volumetric similarity again. The energy transfer from the air flow to the valve movement, calculated both from the amplitude and the phase lag, are plotted in Figure 6c, where the positive suggests a self excitation and the negative suggests a damping, due to the discharge port dynamic flow.

FREE VIBRATION TESTS

A free vibration test for the reed valve was carried out to ultimately confirm the volumetric similarity. Instead of the magnetic exciter in the forced vibration model shown in Figures 1 and 2, a reed valve with a thickness of 0.381 mm, shown in Figure 3, was mounted on the valve plate, without any valve lifter. The left-hand side of the reed valve has the same diameter (12 mm) as that of the valve (column) used for the forced vibration test. The right-hand side was mounted on the valve plate. The natural vibration frequency of the reed valve, F_a, was 200 Hz. The mean pressure in the cylinder was set at the same value (4.9 kPa) as that in the forced vibration tests, and the vibratory behavior of the reed valve was observed. Initially the reed valve was constrained by a holder so as not to vibrate. The transient vibration of the reed valve, which occurs after the holder is released, was measured using a noncontact-type displacement transducer, so as not to disturb the valve. The similar measurements for free vibration of the reed valve were performed for various cylinder volumes from 60 cc to 330 cc.

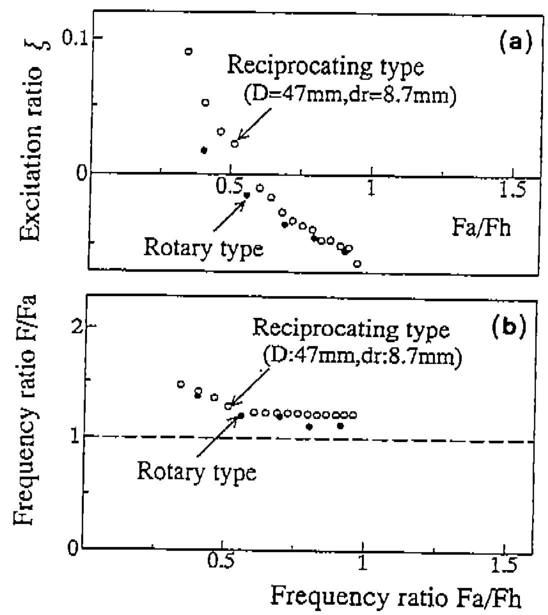

Figure 7. Free vibration test results of the reed valve both for the reciprocating-type and rotary-type resonator model: (a) excitation ratio; (b) in-flow vibration frequency.

With the use of the measured analog data for free vibrations, the vibration frequency F and the excitation ratio ζ_e were calculated and the results were plotted in Figure 7, where the abscissa is the frequency ratio of the natural vibration of the reed valve to the in-flow resonance frequency, F_a/F_h. The data were plotted by a white circle for the reciprocating type and by a black circle for the rotary type. The discharge port reduction ratio ξ was 0.079 for the rotary type, while 0.185 for the reciprocating type, since the free vibration test data were only for the cylinder bore D of 47 mm. Due to this difference in reduction ratio ξ, Figure 7a shows a slight difference in the excitation ratio, while Figure 7b shows a good agreement in the in-flow vibration frequency. In most cases of vibration of a bluff body in fluid flow, the vibration frequency generally becomes lower than the natural frequency due to the effect of fluid-added mass, as studied for the flow-induced vibrations of hydraulic gates, for example, by Ishii *et al.* (1995 /4/). However, it is interesting to note that the in-flow vibration frequency is larger than the original natural vibration of the reed valve. This result suggests that the discharge port flow has a negative added mass effect upon the reed valve vibration.

CONCLUSIONS

In this paper, forced vibration tests for the reed valve exposed to an air jet from the rotary-type resonator model were performed to measure the responding pressure pulsations at the discharge port, where the reed valve was forced to vibrate at a small amplitude of 25 μm and at the frequency from 50 Hz to 500 Hz. Comparing the measured pressure pulsations at the discharge port with those for the reciprocating-type resonator model, the volumetric similarity that the phase lag and amplitude show the similar features if the Helmholtz in-flow resonance frequency is same, was definitely confirmed between the rotary and reciprocating types which have the same value for the discharge port reduction ratio. Additionally, free vibration tests of the reed valve were performed and the volumetric similarity in its excitation ratio and in in-flow vibration frequency was qualitatively confirmed between the reciprocating and rotary types.

It was suggested that the discharge port reduction ratio to the cylinder depth for the rotary type and to the cylinder bore for the reciprocating type has a significant effect upon the contraction of flow at the discharge port, the dynamic response of which is a key factors to determine vibrations of the reed valve. More detailed experimental studies are needed for this subject.

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